ESD-TR-67-391

MTR-256

A PRIORITY MODEL FOR FLIGHT OPERATIONS PLANNING

SEPTEMBER 1967

L. Suyemoto

Prepared for
DIRECTORATE OF PLANNING AND TECHNOLOGY
DEVELOPMENT ENGINEERING DIVISION
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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Project 7070
Prepared by
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FOREWORD

This technical report was prepared by the Applied Mathematics Department of The MITRE Corporation, Bedford, Mass., 01730, under Contract Number AF 19(628)-5165.

REVIEW AND APPROVAL

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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ABSTRACT

The concept of priority is used in many contexts and in many fields. A priority model for priority problems arising in diverse contexts and fields will be established. In this report, the application of the concept of priority is made principally with respect to Flight Operations Planning (FOP) of a manned spacecraft.

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GLOSSARY OF TERMS

Activity	An action to be performed which cannot be partitioned or sub-divided practically into sub-actions.
Conflict Detection Process	A scheme which detects conflicts or incompatibilities (logical, time, resource conflicts) among <u>activities</u> or <u>tasks</u>.
Conflict Planning	The prescription of alternatives whenever a conflict is met within the FOP process i.e., whenever an <u>internal source or condition</u> is met.
Contingency Planning	The prescription of alternative plans whenever an <u>external source or condition</u> is met.
Dynamic Priority Function	A <u>priority function</u> associated with in-flight FOP process. It is a function which may change from time point to time point of the (actual) mission time line depending on the past history of the mission and the environment and the status of the mission at the time point considered.
Exact FOP (Scheduling)	The process by which start and finish times of <u>activities</u> or <u>tasks</u> are established.
External Source or Condition (as related to <u>Contingency Planning</u>)	An emergency or contingency which prevents the performance of a scheduled <u>activity</u> or <u>task</u>. It is external, with respect to the FOP process, in the sense that the emergency or contingency is other than logical, resource or time conflict or that arise within the FOP process.
Internal Source or Condition (as related to <u>Conflict Planning</u>)	A logical, time or resource conflict or incompatibility which arise within the FOP process.

Meta-Selection Function	An override priority function or a last resort priority function which selects an element among elements in conflict or completion whenever all other selection processes fail. This priority function will usually be man.
Priority Function	A generic name for the different types of priority functions. The context in which it is used will determine whether a priority value function, selection function, or meta-selection function is meant.
Priority Value Function	A function which attaches some preference or utility value to elements, such as activities, being considered.
Relative FOP	A process which selects activities or tasks to be performed together with their relative order of performance.
Selection Function	A function which chooses an element from among elements in conflict or competition.
Static Priority Function	A priority function associated with pre-flight FOP. The forms of the functions will, in general, remain fixed during the generation of a nominal (pre-mission) schedule.
Task	A set of activities related to one another in the sense of accomplishing some objective, e.g., an experiment.

SECTION I

INTRODUCTION

1.1 GENERAL REMARKS

The concept of priority is used in many contexts and in many fields. In this report, the application of the concept of priority will be with respect to Flight Operations Planning (FOP) of a manned spacecraft. This is because this study of a priority model originally arose from a study of the priority problem with respect to FOP. It is felt that if a priority model can be established for FOP, then the application of it to other fields will follow as a consequence of re-interpreting the model.

Among the meanings of "priority" given in the Webster dictionary are "any preferential rating assigning rights to scarce products or prescribing the order in which assignments are to be made." Meanings of priority as used in Flight Operations Planning (FOP) are considered, essentially, to be the same as those given in the dictionary.

Priority with respect to FOP is considered as a mathematical function which will be called the priority function. The domain on which this function is defined will be a set X, considered at time t, which contains elements that are in conflict or in competition (for example, with respect to FOP, a set of activities being considered at time t which may be competing for an interval on the

schedule time line). An element of the domain can be written as a pair $(\underline{x}, t)$, $\underline{x} \in X$, where $\underline{x}$ is an n-tuple $(x_1, x_2, \cdots, x_i, \cdots, x_n)$, i can take values $1, 2, \cdots, n$ and where t is the time. In this paper, time t (Section II) is considered as the independent variable and $\underline{x}$ as an index or a parameter. Thus, if f is a priority function, the value of the priority function of argument $(\underline{x}, t)$ is written as $f_{\underline{x}}(t)$, i.e., the priority function is a function of time t indexed or parametrized by $\underline{x}$. Properties of the elements comprising the domain will determine the types of priority function being considered. Similar to the dictionary definition given in the previous paragraph, two types of priority functions are considered. One type is categorized as the <u>selection</u> or <u>"choice" function</u> (order of assignment) and the other type is the <u>priority value function</u> (preferential rating). Depending upon the type of priority function, the range of the function can be the set of non-negative real numbers (for purposes of this paper, the set of non-negative integers is adequate) or the set of conflicting elements (Section II). These two types of priority functions are defined in Section II.

Consider the priority function defined on a set of activities competing for an interval on the schedule time line (or a class of sets, each set comprising a task, competing for an interval on the time line). Two activities could be competing for an interval on the time line not only because of the lack of resources or time to perform both activities but also because the mission objectives have

been changed and a choice has to be made about which of the two activities (or sets of activities) will best reflect the change. The priority value functions give values (ratings) to the competing activities whereas the selection function chooses from among the activities. If the conditions are right (e.g., the necessary resources are available), the selection may be merely the activity with the highest priority value. However, the criterion used for the selection need not be only the priority values but may include factors such as further opportunities to schedule one or the other activity, past history of the flight, probability of success in completing the activity if scheduled, etc. A list of these possible criteria is given in Section II. Each of the different criteria or a combination of them can be a basis for a selection function. For example, the criterion for selecting an activity may be that of choosing the activity with the highest priority value while another criterion could be that of choosing the activity with the highest probability of successful completion.

Circumstances may arise in which a choice of a selection function must be made. Essentially, this means that two or more criteria are in conflict. This situation would be obtained if the condition of the flight at a particular time point makes applicable two or more criteria for selection of an activity among activities in conflict or makes the choice criteria to use ambiguous. For example, at a particular time, t , the two criteria (selection

functions) given in the previous paragraph may have been prescribed to be operative. This situation could also be obtained if the current status of the flight dictates a change in the selection function because of a change in the mission objectives. This latter case requires an override function. In these cases, a meta-selection function is needed. The primary meta-selection function will be man. In the case of in-flight schedule generation, the mission director and/or astronauts will be the final selector. For pre-flight FOP, the flight planners will normally act as the meta-selection function.

The objective of the priority function is to aid in selecting the set of activities to be scheduled. Certainty that the set of activities chosen by means of the priority function can be in reality scheduled is not implied. The processes of selecting a set of activities to be scheduled, conflict detection and resulution schemes [1,2,3], relative FOP (planning) and exact FOP (scheduling) drive one another to generate a feasible flight plan.

In this paper, the term "priority function" will be used generically to mean either the priority value function, the selection function or the meta-selection function. The context, i.e., the specification of the domain and range, in which the term is used will indicate which function is meant. By different specifications of the domain, heuristics (defined in [2]) and mission rules are included as a subset of a set of priority functions. The purpose of the priority function is to aid in resolving conflicts.

Time relations described in [1], such as the precedence relation (activity x precedes activity y) between activities, can be considered also as selection functions. This precedence relation reflects the fact that as a logical consequence of how a task is to be accomplished, activity x must be finished before activity y is initiated, i.e., the duration time of activity x precedes the duration time of activity y on the time line. Precedence between activities x and y with respect to priority means that activity x must be scheduled instead of activity y, i.e., activity x and activity y are in competition for an interval on the schedule time line and activity x is selected, according to some criterion (selection function), to be scheduled rather than activity y. There is this distinction between the relation of precedence with respect to time relations and precedence with respect to priority which must be kept in mind.

The problem and difficulty in the priority problem is the explicit specification of the priority function, viz. the forms of the priority value functions and especially the selection functions. The form of the selection function is dependent on many factors. Some of these factors are listed in Section II. For FOP, the explicit specifications depends on the criteria to be used and on the specific area of the FOP that is being considered. In general, the form and the specification are dependent on the system or purpose for which the priority function is to be applied. A list of some possible

criteria for establishing the form of the selection function is given in subsection 2.2.

Variableness in the values that a priority value of an activity may take, 0 to a mandatory value, say ∞, as well as the variableness in the form that a priority value function may take from time point to time point, may make the specification of the priority value function of some activities difficult. However, for activities that are periodic (Section III) or repetitive during the course of a mission, e.g., sleep cycle for a crew member, a step function or some non-decreasing function over an interval of time can be prescribed. For example, increase in the priority value follows as the number of time units from the last period of sleep for a crew member increases. Once the periodic activity (such as sleep) is performed, the priority value for this activity is decreased and the pattern of the step function or non-decreasing function is repeated over the next interval of time. Different forms of the priority value functions are given in subsection 6.1.

Priority functions used in the context of pre-flight FOP and in-flight FOP can be different. Usually for pre-flight FOP, the priority function forms will vary little and hence can be considered static whereas for in-flight FOP the variability of the forms may be drastic. Static and dynamic priority functions are discussed in subsection 1.2.

The reason that it is desirable to define priority as a function and formalize as much as possible the concept of priority is to make the process of selecting a set of activities to be scheduled amenable to automatic processing. The fact that one knows that the process of conflict resolution (priority functions including heuristics and mission rules) cannot be fully automated (man is an integral part of the process) makes it more cogent that limits are established so that decisions by man are needed only a minimum number of times.

Subsection 1.2 of this paper discusses the application of the priority function in different contexts of FOP whereas subsection 1.3 discusses diverse fields (including FOP) where priority functions are applied. Section II defines, generally, the priority function, the priority value function, the selection function and the meta-selection function. The remaining sections of this paper are concerned with sets of activities and the priority functions operating on these sets. Some explicit forms the priority value function may take are given in subsection 6.1. The final forms of the priority-value function, denoted as the overall priority value function, which are used to determine the overall priority value of an element and which take into consideration whether necessary conditions, e.g., resources, are available, are given in subsection 6.2. A glossary of the more often used terms begins on Page vii.

1.2 DIFFERENT CONTEXTS OF FOP IN WHICH PRIORITY FUNCTIONS ARE APPLIED

To remove ambiguities on the meaning of the priority function, the context in which the term is being used must be specified. Priority function used in the context of pre-flight FOP, in-flight FOP, conflict planning and contingency planning would have different forms and criteria for selection. Discussion of these different contexts follow.

1.2.1 Similarities and Differences Between Static and Dynamic Priority Functions

A distinction must be made between the priority function used in the context of pre-flight FOP and the priority function used in the context of in-flight FOP. In general, the objective of the priority function is the same for both (the objective being the "best" selection of a set of activities to be scheduled). What is different is the manner in which the specification of the priority function is made.

For pre-flight FOP, the priority function can be considered as static since the external conditions are assumed not to change. This is not to say that priorities do not change over the time line considered but the forms of the priority functions are prescribed beforehand. For example, for an anticipated contingency (malfunction of an equipment) the priority function will depend on the severity of the contingency and/or where on the schedule time the contingency occurred. The degree of severity will be determined by

the extent to which the mission goals or objectives are compromised. The selection of the "best" set of activities to be scheduled at a particular time t is dependent on many factors and hypotheses. If the hypothesis is, for example, that at a particular time a power loss occurs, the priority functions to be used will certainly reflect this hypothesis but other factors will be considered as known or unvarying. In this manner, via a computer simulation or an actual simulation, the effect of the contingency (power loss) can be determined. Thus, the form of the priority function is dictated by the objectives and goals of the mission and on hypotheses that there are no other contingencies other than the one being considered and other external conditions are constant or known.

The objective of pre-flight FOP (relative FOP and exact FOP) is to obtain a nominal schedule, i.e., a flight plan. This nominal schedule is for the duration of the entire mission. It is a plan which can be described as that which under the best guess, knowledge, experience and conditions is one that can be followed. It is a plan which, if followed, fulfills all (pre-flight) mission objectives and goals. In reality, it is a plan for which there is little likelihood of being "exact," i.e., every task occurring as scheduled. The generation of a schedule even for a time duration of only two or three days which has a relatively high probability of being exact would be a remote possibility (assuming that the schedule for the two or three days has tasks for the crew other than merely "floating" in space).

Thus, a nominal flight plan is one which fulfills, theoretically, all the objectives and goals of the mission. It is that schedule which after a mission is completed, one can compare and note where mission goals and objectives were not fulfilled and where they had to be modified. The nominal schedule obtained by pre-flight FOP is a base or standard by which the completion (or incompletion) of the mission goals can be measured.

In contrast with pre-flight FOP, in-flight FOP may necessitate changes in the priority functions, different from those prescribed by pre-flight FOP, from time point to time point. This may be necessary because of unanticipated contingencies, external conditions and environment not expected or activity and/or task durations given by pre-flight FOP not being realistic. Any one of these factors occurring may change or modify the mission goals and objectives. In order to accomplish these changed goals, priority functions may have to be changed at each time a look-ahead schedule is being generated. Since the forms and values of the priority functions may change with time (the priority functions being dependent on the current condition and environment of the flight), the priority functions can be considered as dynamic in in-flight FOP. Also, in comparison with pre-flight FOP, the variability or change in the forms of the priority functions in in-flight FOP will be more extreme.

For in-flight FOP, the generation of a schedule is done for a relatively short look-ahead period of time (time window).

In addition, an evaluation of the schedule for this period of time should be made with respect to its effects or possible effects on the schedule for the remainder of the mission. This look-ahead schedule must also be considered nominal although the probability that it can be carried out as scheduled is much greater than the nominal schedule obtained from the pre-flight process. The nominal look-ahead schedule for a future time window would be updated at different time points. Obviously, there is a certain cut-off time before the first activity in the look-ahead schedule is to occur when updating must cease. This is in distinction to the (near) real time scheduling where scheduling is done on the activity level. The (near) real time scheduling would be the scheduling of an activity and while this is being performed the scheduling of a subsequent activity is taking place. A case where this (near) real time scheduling would be required is when a conflict or contingency is met in the schedule as it is being performed. It is possible that an activity or task already in progress could be prematurely terminated because of a contingency or because of a decision by man. In the latter case, the override or meta-selection function is operative. For example, an astronaut performing an experiment (docking) may encounter an unanticipated contingency (instability of the spacecraft). The astronaut in this case may have to "fly by the seat of his pants," interrupting the experiment and initiate a new activity to overcome the contingency. In this case, the astronaut is scheduling the next activity (perhaps a maneuver) with support from the ground or co-astronaut or independently using his own judgment.

As the nominal look-ahead schedule is being updated and changed, these changes will also indicate to mission controllers the potential weaknesses and critical areas in the schedule. Knowing the past history of the flight and status of the mission, modifications in mission objectives may be necessary. These modifications will affect future look-ahead schedules because the priority functions will be changed.

1.2.2 Priority Functions With Respect to Conflict Planning and Contingency Planning

Conflict planning pertains to conflicts which arise within the processes of relative FOP and exact FOP. It is internal in the sense that conflicts may arise among activities with respect to their time relations and/or time durations. The alternative time relations or duration time chosen whenever there exists a conflict are those that are valid within the constraints imposed, such as keeping certain time relations fixed or keeping the duration time of activities within certain bounds. Conflict planning aids in the generation of feasible schedules assuming the external conditions are known, predictable, or non-varying.

Contingency planning on the other hand pertains to relative FOP and exact FOP whenever a scheduled activity or task cannot be performed because of an emergency or conflict created by an external source, i.e., outside the FOP process. In pre-flight FOP, the contingencies are anticipated emergencies such as a sudden breakdown in equipment. Contingency planning in this case would give

alternative plans or objectives depending on the seriousness of the contingency or merely modify the activities and/or time relations. If an anticipated contingency does occur in flight, an alternative plan can be selected based on, for example, mission rules. In-flight unanticipated contingencies, such as a sudden equipment failure, can occur. The contingency may necessitate modification of the objectives of the mission or a change in the current schedule. The former case will lead to modifications in future look-ahead schedules. A change in the current schedule may necessitate (near) real time scheduling or modifications of the activities to be performed. If the contingency is serious, as endangering the crew, then an abort sequence would be followed. Priority functions associated with unanticipated contingencies will be the meta-selection function, usually man.

1.3 APPLICATIONS OF THE CONCEPT OF PRIORITY

The concept of priority is used in many diverse fields (as a matter of fact, it is a concept used in everyday life by most people). It is used for customer service in stores, in multi-user computer systems and in FOP. In each of these fields, the priority value function, the selection function, and the meta-selection function are in operation.

For example, consider the case of a store. In this case, the objectives of a priority scheme are to minimize the congestion in the store and to have customer waiting time a minimum. This can be accomplished by expediting the check-out of the customers. The

customers are given tags which bear a number. These numbers are the priority values, and the procedure by which each of the customers receives a number is the priority value function. It should be noted that in this simple example only the numerical (ordinal) values are considered. The concept of the utility (weight) values (subsection 2.1) is not used. The selection function or priority rule usually is "first come-first served," i.e., the customer with the smallest number is served first. The override or meta-selection function may be the store manager who may override the selection function by giving preference to a customer with a higher number. His criterion for doing so may be that the customer is a friend of his.

As the system in which priority functions are to be applied becomes complex, the priority functions are more complicated. Nevertheless, the general procedure given in the example of the store is essentially the same.

For FOP, the priority function can be considered as a filter. Initially, given a set of activities that needs to be scheduled, it aids in selecting a subset of this set upon which the scheduling processes are to be applied. It precedes such processes as conflict detection that leads to a schedule. If the subset of activities selected cannot be actually scheduled, the priority functions select another subset of activities and all processes of scheduling are again applied. This procedure is repeated until convergence upon a feasible schedule is accomplished.

The forms of the priority functions are dependent on the objectives of FOP. Moreover, they are intimately related to the processes that lead to such an objective, i.e., the generation of a feasible schedule that fulfills mission goals is a consequence of the processes of conflict detection and resolution, resource allocation, etc. Some of the general forms of the priority functions will result from the processes that lead to obtaining a feasible schedule. Heuristics as given in [2] are examples.

Implementation of a priority scheme, in practice, requires the knowledge of the details of the system to which it is being applied. For example, for FOP, knowledge of the following details may be required:

(a) how the data base is formed;

(b) resource limits;

(c) processes of scheduling, such as conflict detection schemes and resource allocation schemes;

(d) mission objectives, e.g., experiments, and requirements of time and resources to accomplish these objectives;

(e) mission rules; and

(f) orbital characteristics of the flight.

If the details of the system are known or given, different priority functions can be prescribed and integrated with the processes of scheduling.

SECTION II

PRIORITY FUNCTIONS

Classification of the priority functions with respect to FOP is made by making a distinction between a selection or choice function and the priority value function. Two sub-types of selection or choice functions are distinguished by the domain and the range of the functions. These two sub-types are called the <u>selection function</u> and the <u>meta-selection function</u>. These classes of priority functions will now be defined in the following paragraphs.

Let X be a set. The elements of the set X can be activities, time relations or alternate flight plans (sets of activities). Within this set are elements in some form of competition or conflict.

If the elements of the set X are activities, then within this set are activities competing for an interval on the schedule time line or for resources that are available in a particular interval of the schedule time line. For example, two activities could be competing for the same interval on the schedule time line but cannot be simultaneously scheduled in this time interval or two activities could be competing for the same resources but the resources are inadequate for both activities to be scheduled. If the elements of the set X are time relations, a subset of X could be a set of valid time relations which resolves a logical conflict in relative FOP [1,2]. (A heuristic or choice function may be prescribed to choose the time relation to use.) If the elements of the set X are sets of activities, a subset of the set X could be alternate plans for

resolving a contingency. (Mission rules and/or heuristics would select the alternate plan.)

Call the set of competing elements or elements in conflict, A, i.e., $A \subset X$.

2.1 PRIORITY VALUE FUNCTIONS

In subsection 6.2, there is defined the overall priority value function. This function is a function of time and is indexed by x where x is an element of A and written as $P_x(t)$. The values of this function will be called overall priority values. The overall priority value function is dependent on certain conditions being obtained, e.g., resources available (Section 4.0) and two functions p_x, p_x^{μ}. These two functions will be generically called priority value functions (without the word overall preceding) and will be discussed in the following paragraphs.

There is associated with each element of $A \subset X$ an overall priority value function with the domain of this function being the time line, i.e., the independent variable is t, (see subsection 1.1) and the range of the function being the non-negative real line (non-negative integers will suffice). The overall priority value function gives the (overall) priority value of an element of A at a particular time or for an interval of time under consideration. For example, the (overall) priority value for the activity "sleep" will be low if the astronaut has just awakened.

Priority values obtained from the priority value function can be categorized to be of two types. One type of priority value is strictly a numerical (ordinal) value whereas the second type is the utility value. The ordinal values may be just numbers which orders the elements to be considered as first, second, etc. The utility values on the other hand gives an indication of the relative importance of the elements, e.g., in successfully fulfilling an objective or the probability of doing so. Initially, the utility values may be only qualitative such as important, very important. However, these utility values can be quantified by giving them numerical values (weights) which indicate their relative importance. Thus, the overall priority value of an element, assuming all required conditions are obtained can be generally given by the sum or product of the utility value and the ordinal value. Both types of priority values need not be always used. Each type can be used independently, or numerical values can be given which indicate both the ordinal values as well as the utility value. An example of the latter is given at the end of this Sub-section. Thus, in speaking of priority values, the distinction between the two types must be kept in mind. To make it notationally easier, $p_x(t)$ will be used to mean either type but $p_x^{\mu}(t)$ will be used to mean the utility value if there is any chance of confusion as to which is meant.

If a set of activities at time t is considered as the domain, the priority value function gives for each activity to be

scheduled a priority value for a future time window for in-flight FOP or for a nominal schedule for pre-flight FOP (Sub-section 1.2). If a set of time relations at time t is considered as the domain, the priority value function gives the priority value of the time relation to resolve a logical conflict. For example, a heuristic (such as those defined in [2]) may give a number of time relations possible to resolve a logical conflict. The priority value of each of these relations, being considered at time t, may be prescribed by the heuristic which gives the preferred order of the time relations to use to resolve the conflict. If a class of sets of activities (plans) at time t is considered as the domain, the priority value function gives the priority value of each set to resolve a contingency. The class of plans can be given priority values, an ordering such as 1,2,... denoting the preference (utility value) of one plan over another in fulfilling a mission objective in spite of the contingency. The priority values are time dependent. For example, if the contingency is a loss of power due to malfunction of an equipment, the priority values of the alternate plans are dependent on the time when the contingency occurred. The priority values of the plans will reflect whether the power loss occurred early or late in the mission.

The time t or the time interval being considered can be with respect to the real time line (the origin, say, the time of the launch) for in-flight FOP or the relative time line for pre-flight FOP (the origin being some chosen as the point from which time is to be referenced).

To make the definition more precise, the following terminology and notations are used. The set $A \subset X$ can be considered as an index set (see subsection 1.1). For each $x \in A$ there is associated a priority value function of x at time t, denoted as $p_x(t)$, such that

$$p_x(t) = c \tag{1}$$

where $c \in [0, \infty]$ (or c is an element of the set of non-negative integers). The set of priority functions associated with $A \subset X$ is denoted by P_A.

Interpretations of the numerical value c can be given as a measure of the importance of the element (or a set of elements) or merely to be an ordinal number. The value of c thought of as only a utility value can be considered as a weighting factor. However, the value of c can be also interpreted as a combination of both the ordinal and utility value as follows. A mandatory value of performance or of importance of an element x may be denoted by ∞ or a very large number Q. The range of values for non-mandatory elements will be in the finite interval $[0, Q]$. A scale of values must be given on $[0, Q]$ which correspond to the importance (utility) attached to an element of A at the time t under consideration. For example, a simple scale would be

Mandatory	Q(>100)	
Very Important	100	
Important	70	(2)
Not so Important	40	

The scale would be a function of time. For example, an activity given a priority value of 40 at time t_1 may have been assigned that value because there were further scheduling opportunities. At a later time t_2, this activity may have a rating (priority value) of ∞ (or Q). For some elements, the designation of the scale (the range of $p_x(t)$) would be imposed by man (especially for in-flight FOP). For periodic and repetitive activities, such as sleep for a crew member, the priority values can be generated in functional form (Section VI).

2.2 SELECTION FUNCTION

From the set $A \subset X$, a set M of ordered n-tuples, $n \geq 2$, can be formed. The coordinates of an n-tuple are those elements which are competing (say, for the same time slot on the schedule time line) or are in conflict. Associated with each n-tuple is a selection function, i.e., the domain of the selection function is the n-tuple and the range is the set consisting of the elements of the n-tuple. For example, suppose that $n = 2$ and there is given an ordered pair $(x, y) \in M$. The value of the selection function is either x or y (but not both).

Certainly one selection will not guarantee a schedule. If the n-tuple is an n-tuple of activities, the choice made does not guarantee a feasible schedule. The scheduling processes, e.g., conflict detection schemes, must be performed on the set of activities chosen. If the n-tuple is an n-tuple of time relations, the selection

of a time relation (via a heuristic [2]) does not necessarily mean that the choice made would resolve a logical conflict (unless the choice comes from a set of valid time relations [1]). The choice made will have to be verified by the conflict detection and resolution schemes [2]. If the n-tuple is an n-tuple of sets of activities (n-tuple of alternative plans), the choice made does not guarantee that the contingency will be circumvented or resolved. This will have to be verified by means of relative FOP, exact FOP, and also by a check to determine whether the alternate plan chosen does not lead to conflicts in the future.

Like the priority value function, the selection function is a function of time, denoted analytically as

$$s_{\underline{m}}(t) = m_i \tag{3}$$

where $\underline{m} = (m_1, m_2, \ldots, m_n) \epsilon M$. Another way the selection can be defined is to consider the set of coordinates of the n-tuple $\underline{m} = (m_1, \ldots, m_n)$ at time t to be the domain and the range to consist of the integers 0 and 1. Then Eq. (3) can be written as

$$s_{m_i}(t) = 0 \text{ or } 1 \tag{4}$$

where the value 0 means that m_i is not to be selected and the value 1 means that m_i is to be selected.

At one time, the form of the selection function, say, for an ordered pair $(x, y) \epsilon M$ may be only a comparison of the overall priority values given by the overall priority value functions at this

time. The element chosen is that which has the higher overall priority value, e.g., x if $P_x(t) > P_y(t)$. However, this criterion of choice will differ if the chosen element does not lead to a feasible schedule or resolve a logical conflict or contingency. In this case, another selection function must operate on the ordered couple. There may be more than one alternate selection function when this condition is obtained depending on the status of the mission at this particular time. Other instances can easily arise when for a particular time and an ordered n-tuple of the set M, more than one selection function is possible. Thus, there may be a set S of selection functions for an ordered n-tuple of M at a particular time t.

The criteria used for the selection function can vary tremendously. The selection functions which could be automated are those of the conditional or propositional forms. This assumes that a list of pertinent criteria (involving factors listed in 2.3.1) has already been established. Considering the priority function definition in the general sense, these criteria would include mission rules and heuristics. The conditional forms would be of the type "If ... then ...", i.e., among those elements which are in competition or conflict, choose the element which meets the "if" condition.

2.2.1 Selection Criteria

Selection criteria could include:

(a) Select the element with the highest priority value at time t.

(b) Select the element with the highest likelihood or probability of being successfully accomplished if certain conditions are obtained. (This criterion sets more emphasis on the success of the completion rather than on the priority values of the competing elements).

(c) When a certain condition is obtained, select a particular element. If the condition is not obtained then make an alternate selection. (Heuristics for choice of different elements.)

(d) If an anticipated contingency is encountered and certain conditions are met, select a certain alternate plan.

(e) (Anticipatory selection criterion.) If the selection of an element x does not jeopardize the accomplishment of element y in a future time window, then choose element x .

2.3 META-SELECTION FUNCTION

For the set S of selection functions defined in the previous sub-section, a meta-selection function which chooses a selection function for use at time t is required. The domain of the meta-selection function is S (at time t) and the range is S . In analytic form

$$n_S(t) = s \ , \ s \in S \qquad (2.3\text{-}1) \qquad (5)$$

2.3.1 Determination of the Form of the Meta-Selection Function

Some variables and factors which are candidates for consideration in determining the form of meta-selection functions are:

(a) orbit number and orbit geometry,

(b) position of the vehicle,

(c) resources available,

(d) resources depleted,

(e) rate of resource depletion,

(f) objectives and goals of tasks to be scheduled,

(g) objectives of the mission,

(h) medical status of the crew,

(i) past history of the flight,

(j) experience acquired during previous and current flights,

(k) future opportunities for scheduling,

(l) established mission rules,

(m) heuristics,

(n) current status of the mission,

(o) probability of success of accomplishing tasks,

(p) contingencies anticipated,

(q) time (current) of the mission, and

(r) contingencies not anticipated.

It should be noted that <u>all</u> factors and variables pertinent to the success of a mission or the accomplishment of an objective must be considered in determining the form of the meta-selection function. The meta-selection function is the override function. The most important form of this function is man or men. In pre-flight FOP it will be the planning director and for in-flight FOP it will be the flight director and/or astronaut who will act in concert as the meta-selection function when all other selection processes fail. Man, in the role of a meta-selection function can be aided by the computer which can present to him alternate choices and help him decide, by testing, whether a particular choice of an activity (or plan) is feasible or not. For those cases which are not accounted for and formalized (unanticipated contingencies or where selection functions are not prescribed) man must act as the meta-selection function.

The main areas where meta-selection functions would be required are:

(a) unanticipated contingencies,

(b) changes in the mission goals and objectives, and

(c) absence of selection criteria.

SECTION III

CLASSIFICATION OF TASKS AND ACTIVITIES

The remainder of the paper will be concerned with sets of activities and the priority functions operating on these sets.

A list of tasks and activities that are usually performed on a manned space mission is given. These tasks and activities have to be scheduled, and if certain tasks or activities are competing for the same time interval on the schedule time line, the conflicts can be resolved by using the priority functions.

Most of the tasks listed are periodic or repetitive. They must be performed a number of times daily, a number of times per orbit, or a number of times during the mission. Four broad classifications of tasks are made: tasks pertaining to the crew, communications, spacecraft, and the mission goals and objectives.

3.1 TASKS PERTAINING TO THE CREW

Let C_1, C_2 denote the crew members. (The generalization to more than two crew members can be easily made.) Let $C_1 \vee C_2$ denote that either one or the other of the crew members is required and $C_1 \wedge C_2$ denote that both crew members are required for a task. The tasks which relate directly to the physical welfare of C_i are usually periodic. They are:

(a) sleep,

(b) personal hygiene,

(c) preparation of food and eating, and

(d) biomedical tests.

3.2 TASKS PERTAINING TO THE SPACECRAFT

Let E_j, $j = 1,2...,n$ denote the different equipment on the vehicle. The tasks relating to the equipment on board the spacecraft are

(a) maintenance of equipment,

(b) equipment (system) monitoring (bookkeeping of the different equipment such as reading dials, checking vehicle stability, attitude, position, checking availability of resources and the rate of depletion of resources), and

(c) life support equipment (system) monitoring (bookkeeping on the availability or depletion of life support resources).

3.3 TASKS PERTAINING TO COMMUNICATION

The tasks pertaining to communications are categorized as

(a) telemetry dumps,

(b) voice contact between crew and ground, and

(c) receipts of commands from the ground (digital).

3.4 TASKS PERTAINING TO MISSION GOALS AND OBJECTIVES

The tasks pertaining to mission goals and objectives are those which deal with scientific experiments and space operations for which the mission was designed. These experiments and operations will be denoted as $Ex_1, Ex_2, \ldots, Ex_m$.

SECTION IV

AVAILABILITY FACTORS

A task or activity that needs to be scheduled does not mean that it can be scheduled. Whether a task can be considered for scheduling is dependent on certain factors and conditions existing and being favorable, e.g., availability of the required resources. Unless the conditions are favorable, the selection of a task among competing tasks would be meaningless. For each task, then, there exists a set N of conditions. A list of these conditions is given in the next sub-section.

Two concepts of time are being used whenever a set N of conditions is considered. These two concepts are the particular time the set N is considered (the time at which the particular task or activity is under consideration for scheduling on the (schedule) time line and the time in the (schedule) time line for which the activity is being considered. For example, a task may require that crew member 1 perform an activity and upon the completion of this activity, crew member 2 is required to perform an activity. Elements of the set N at time t for this task include the availability of crew member 1 over an interval (duration of the activity to be performed by crew member 1) on the schedule time line and the availability of crew member 2 over another interval (duration of the activity to be performed by crew member 2) on the schedule time line.

An availability factor can be defined as a function whose domain is the set N at time t and whose range consists of the two integers 0 and 1. Value of 1 for this function means a favorable condition and a value of 0 means an unfavorable condition.

4.1 LIST OF AVAILABILITY FACTORS

(a) Availability of Crew

Let A_1 denote the availability factor and C_1, C_2 the crew members. Availability of the crew member for a task to be scheduled on the time line is given by the values of $A_1(C_1)$, $A_1(C_2)$. If both members of the crew are required, the availability or non-availability is determined by the product $A_1(C_1 \wedge C_2) = A_1(C_1)A_1(C_2)$. (One can enumerate the skills of each member of the crew and the function A_1 can operate on this set of skills. This refinement, however, is not necessary since the availability of the skill obviously is determined by the availability of the crew member.)

(b) Availability of Resources (R)

Let $R_1, R_2, \ldots, R_p$ be the resources required for a task under consideration and let A_2 be the availability factor. The availability of resource R_i at time t (for a time window in the schedule) is given by the value of $A_2(R_i)$. Denote the availability of all resources required by $A_2(R) = \prod_{i=1}^{p} A_2(R_i)$.

(c) Availability of Equipment (E)

Let $E_1, E_2, \ldots, E_m$ be the equipment on board required for the task and let A_3 denote the availability factor. The avail-

ability of equipment E_j (for a time window) at time t is determined by the value of $A_3(E_j)$. Denote the availability of all equipment by

$$A_3(E) = \prod_{j=1}^{m} A_3(E_j) .$$

(d) Weather Conditions (W)

Let $W_1, W_2, \ldots, W_q$ denote the different weather conditions (examples, clear sky, day, night) for a task (such as photographic experiments) and let A_4 be the availability factor. The availability of condition W_i is given by the value of $A_4(W_i)$. Denote the availability of all such weather conditions by $A_4(W)$

$$= \prod_{i=1}^{q} A_4(W_i) .$$

(e) Availability of Ground Stations (GS)

Let $GS_1, GS_2, \ldots, GS_r$ denote the different ground stations (or different ground support) required for a task and let A_5 be the availability factor. The availability of GS_i (that can accept, for example, certain types of data or signal or transmit them) required for the task is determined by the value of $A_5(GS_i)$. Denote the availability of all the different ground support by

$$A_5(GS) = \prod_{i=1}^{r} A_5(GS_i) .$$

(f) Conditions Required for the Spacecraft (SC)

Let $SC_1, SC_2, \ldots, SC_s$ denote the different conditions such as attitude, location required of the spacecraft for a task and

let A_6 be the availability factor. That the condition SC_i can be obtained or not is given by $A_6(SC_i)$. Denote the attainment of all the conditions required of the spacecraft by $A_6(SC) = \prod_{i=1}^{s} A_6(SC_i)$.

SECTION V

DIFFERENT DOMAINS OF THE PRIORITY FUNCTION

The priority function is a function of time (Section II). In the context of pre-flight FOP, the time is the current time when the nominal schedule is being considered. For in-flight FOP, the time is the current time of the mission for which a look ahead schedule is being generated. The priority value of a particular activity or task and the criteria of selection between two competing tasks can vary from time point to time point and in the different contexts of pre-flight FOP and in-flight FOP. A task such as an experiment which comprises part of the mission objectives may have a high priority in pre-flight FOP. This same experiment, however, may not be performed because of equipment failure. Thus, for in-flight FOP this experiment may not be even considered for scheduling. The possible high degree of variability of the priority function for in-flight FOP from time point to time point is due to the impossibility of accurately predicting the status of the mission from time point to time point. This in turn makes it impossible to fully automate the priority function. Man must be an integral part of the priority function (the override or meta-function).

The priority function at time t acts on a set of activities or tasks (the domain of the function). Different domains of the priority functions will now be listed along with the type of priority functions operating on them.

5.1 MANDATORY ACTIVITIES

Mandatory activities or tasks are those activities which must be scheduled for the success of the mission or for the safety of the crew. Although a set of activities in pre-flight FOP may be classed initially as mandatory, the actual set of mandatory activities for in-flight FOP at different times is varying. This variance is due to the change in the status of the mission. Certain activities which were not mandatory at a previous time point may at the current time become mandatory.

Priority values attached to mandatory activities being considered at time t will obviously be high. The priority value function over the domain of mandatory activities would have the priority value ∞ attached to the activities at time t or would be constant (with value ∞) over an interval of time t . The selection function would have a fixed criterion of always selecting the mandatory activity if a mandatory activity and a non-mandatory activity are in conflict. If there are two mandatory activities which are competing, for example, both activities may be part of the mission goals, man would be involved as the selection function or if there is a selection function, man would be the override or meta-selection function.

5.2 ACTIVITIES WHICH DEPEND ON SCHEDULING OPPORTUNITIES

Activities which depend on scheduling opportunities can be broken down into two categories. One category is the set of activities which are used to pack the (schedule) time line (for a look

ahead schedule time interval). These are activities such as housekeeping, "free" time that can be performed concurrently with activities that needs to be scheduled (such as a mandatory activity). These activities do not have the relative importance of other activities to be scheduled at time t. Obviously, for this category of activities to be considered, free time in the schedule time window must exist. The second category of activities are those activities which need to be scheduled but can possibly wait until another time window or time interval. This category will include periodic and repetitive activities.

The priority value for activities in the first category will be low. A crew member can act as the selection function, selecting certain alternative activities, or the selection function could be merely the choice of that activity with the higher priority value.

In the second category, the priority values assigned to an activity x competing with other activities for a time interval may be high. Further opportunities, however, to schedule activity x may exist in future time windows. In this case, the selection function may choose another activity with a lower priority value than activity x but with fewer scheduling opportunities in future time windows. The priority value of activity x not chosen may then be increased.

5.3 CONTINGENCY PLANS

For an anticipated contingency, there would be associated alternative plans (sets of activities) to resolve or circumvent the

contingency. The determination of the alternative plans themselves may have involved the use of priority functions. Each of these sets of activities can now be considered to have a priority value. Capability of a particular plan to accomplish the mission goals or objectives in spite of the contingency would be reflected by the priority value. The priority value can be the probability that a particular plan would accomplish the desired objectives. Some scale of the desirability of having a particular objective accomplished could also be used as priority values, i.e., a scale imposed on the set of plans ranging from the most desirable or most important to the least desirable or least important. The scale of values would not necessarily have to imply the realization of the plan.

The probability values and the scale values used as priority values will usually be established before the contingency is met. Obviously, the selection function (before the actual contingency) would select the plan with the highest probability of success or the highest scale value. In-flight dynamically changing conditions may make this selection criterion inappropriate. Criteria that may be necessary to determine the selection function other than those listed in Section II would be principally the severity of the contingency and the extent to which the objectives and goals of the mission and safety of the crew are involved. Reassessment of the probability for success of a plan or scale values reflecting the changed conditions must be made.

5.4 PERIODIC OR REPETITIVE ACTIVITIES

Generated priority values of activities will be defined as those that can be given by a function of time. These priority values can be automatically computed by the function from time point to time point. Those activities for which this is readily possible are activities which are periodic or repetitive. The generated priority values for these activities reflect whether the particular activity has been scheduled or not. A high priority value indicates that the time elapsed since the activity had been scheduled is long. A low priority value signifies that the particular activity had been scheduled in a recent time window. Different possible types of functional forms for obtaining priority values are given in subsection 6.1.

5.5 NON-PERIODIC ACTIVITIES

Activities which were under consideration in a particular time window but were not scheduled can be given higher priority values for processing in future time windows (subsection 5.2). One means of accomplishing this is by the functions defined in subsection 6.1.

There is a possibility that the set of activities which cannot be placed in future time windows will become large and the number of opportunities to schedule these activities decrease or are non-existent. This case could arise, say, if the power of the spacecraft was so drastically reduced by a malfunction in the power system. Certain criteria must be used which allows for the upgrading of the priority values of activities, particularly those which are related

to accomplishing current mission goals and objectives. A certain amount of weeding out of activities must be done. Criteria to do this are, for examples, the penalty (or cost) of not doing a particular activity or the relative importance to the current mission objective of doing an activity versus that of not doing it. By using such criteria, a smaller updated set of activities to schedule may be formed which reflect the current status of the mission. This bookkeeping of the set of activities should be performed periodically.

5.6 SEQUENTIAL ACTIVITIES

Certain tasks may require that activities $x_1, x_2, \ldots, x_n$ be done sequentially in different time windows for the completion of the task. These activities which make up the task may be competing for a time interval or resources in particular time windows. Once the initial activity has been scheduled and performed, the remaining activities must sequentially follow. The completion of the preceding activity in this sequence may set automatically a priority value on the succeeding activity.

An example where sequential priority may be applied is where a contingency occurs. A contingency will have associated with it different alternate sets (plans) of activities. Each plan can be thought of as a sequence of activities, and from a particular activity there can be different branchings to different activities. The sequential priority of the activities is determined as one proceeds through a branch (plan) as each of the activities in the sequence is selected

according to some selection criteria. In this manner, each activity of the plan has been sequentially given a priority value. The sequential priority values attached to the activities subsequent to the initial activity would take precedence over some other competing activity with a higher priority value if the sequence of activities are concerned with mission goals or with the safety of the crew.

SECTION VI

SOME FUNCTIONAL FORMS OF THE PRIORITY VALUE FUNCTION, OVERALL PRIORITY VALUE FUNCTION OF AN ACTIVITY

6.1 SOME FUNCTIONAL FORMS OF A PRIORITY VALUE FUNCTION

Any function which can be explicitly stated and adequately depicts the increase and decrease of the priority values for an activity in question can be used for the generation of priority values. The easiest functional forms are the step functions and the linear functions.

For periodic or repetitive activities priority value functions can be readily defined. They can be defined as discontinuous functions of the entire time line or as discontinuous periodic functions over the time line. Three simple functional forms of periodic functions are shown in Figures 1 through 3. Time scales on the figures may be different. For instance, in Figure 1, the activity considered may be sleep and the time scale may be in 8-hour units. The scales used must be made compatible with the time on the schedule time line.

Analytically, Figures 1 through 3 can be described as shown below.

Figure 1:

$$p_x(t) = v_j \qquad t_{j+3i-3} \leq t < t_{j+3i-2} \qquad j = 1,2,3 \qquad (i = 1,\ldots,n)$$

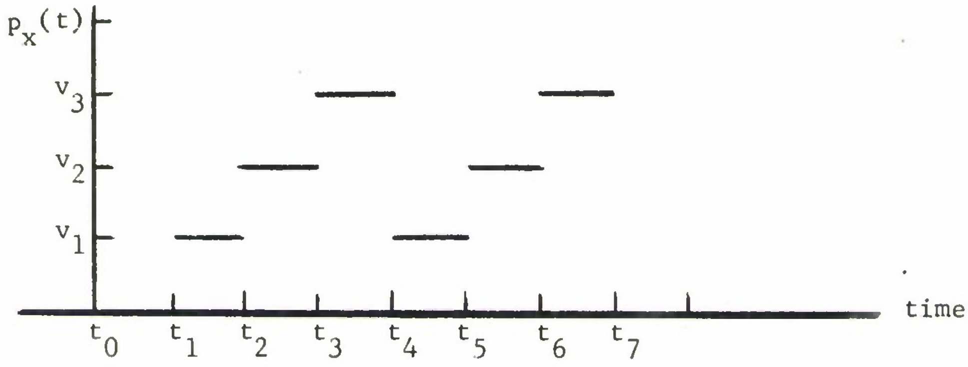

Figure 1. Step Function

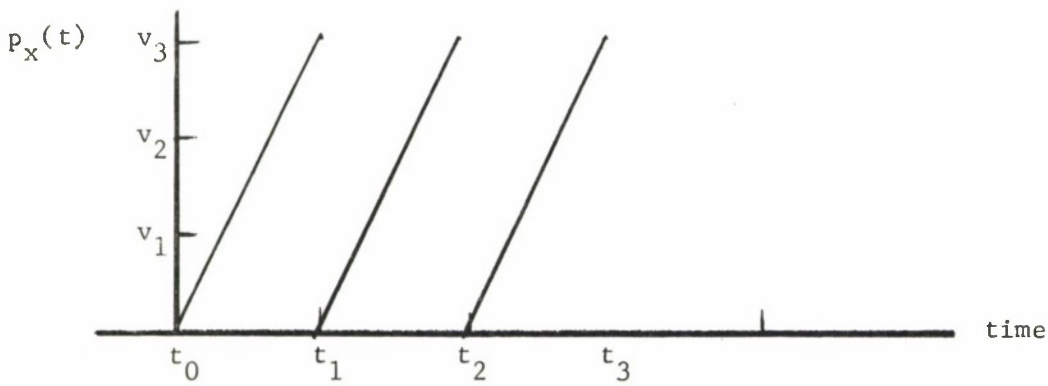

Figure 2. Discontinuous Linear Function

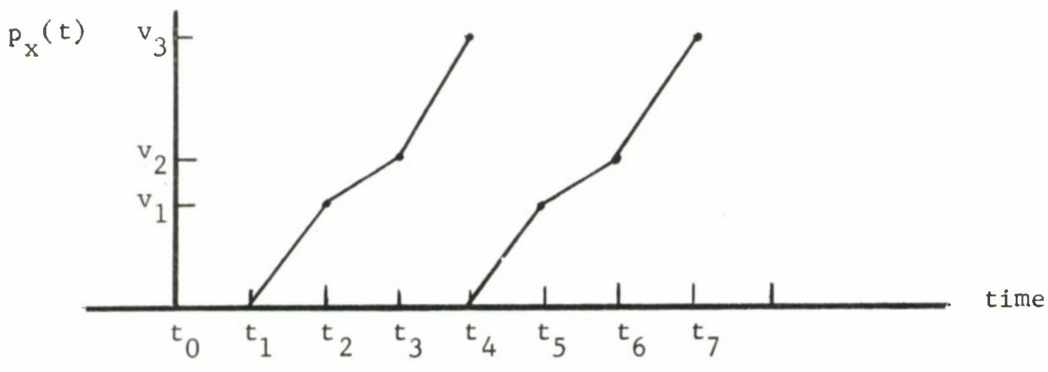

Figure 3. Broken Line Function

Figure 2:

$$p_x(t) = \frac{v_3}{t_{i+1} - t_i}(t - t_i) \qquad t_i \leq t < t_{i+1}\ ,\ i = 0,1,\ldots$$

Figure 3:

$$p_x(t) = \frac{v_1}{t_{i+1} - t_i}(t - t_i) \qquad t_i \leq t \leq t_{i+1}$$

$$p_x(t) = \frac{(v_2 - v_1)t + (v_1 t_{i+2} - v_2 t_{i+1})}{t_{i+2} - t_{i+1}} \qquad t_{i+1} \leq t \leq t_{i+2} \qquad (i\ \ 1,4,7,\ldots)$$

$$p_x(t) = \frac{(v_3 - v_2)t + (v_2 t_{i+3} - v_3 t_{i+2})}{t_{i+3} - t_{i+2}} \qquad t_{i+2} \leq t < t_{i+3}$$

6.2 OVERALL PRIORITY FUNCTION OF AN ACTIVITY

An overall priority value function for an activity x may be written as either

$$P_x(t) = A_1 A_2 \ldots A_6 [p_x(t) + p_x^{\mu}(t)] \tag{5}$$

$$P_x(t) = A_1 A_2 \ldots A_6 [p_x(t) p_x^{\mu}(t)] \tag{6}$$

where

$P_x(t)$: Overall priority value of activity x at time t.

$p_x(t)$: Priority value of activity x at time t (generated or assigned).

$p_x^{\mu}(t)$: Utility factor imposed with the priority value, additive in Eq. (5) and multiplicative in the other case. For example, this factor could be derived from the probability of success of performing the activity. This factor is used to increase or decrease the priority value of an activity.

A_i : $i = 1,\ldots,6$, availability factors discussed in Section IV.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The MITRE Corporation Bedford, Massachusetts	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
A Priority Model for Flight Operations Planning

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
N/A

5. AUTHOR(S) (First name, middle initial, last name)
Suyemoto, Lee

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1967	51	4

8a. CONTRACT OR GRANT NO. AF 19(628)-5165 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) ESD-TR-67-391 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) MTR-256

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Directorate of Planning and Technology, Development Engineering Division, Electronic Systems Command, L. G. Hanscom Field, Bedford, Mass.

13. ABSTRACT

The concept of priority is used in many contexts and in many fields. A priority model for priority problems arising in diverse contexts and fields will be established. In this report, the application of the concept of priority is made principally with respect to Flight Operations Planning (FOP) of a manned spacecraft.

DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
MODELLING Priority Model, for Flight Operations Planning (Manned Spacecraft) PLANNING Flight Operations (Manned Spacecraft), Priority Model MATHEMATICS Priority Model, for Flight Operations Planning (Manned Spacecraft) SPACECRAFT, MANNED Flight Operations Planning, Priority Model						